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**Zhu et al.**

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(54) **STRESS-GENERATING STRUCTURE FOR SEMICONDUCTOR-ON-INSULATOR DEVICES**

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**H01L 21/8222** (2006.01)

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CPC ..... **H01L 29/0603** (2013.01); **H01L 21/76224** (2013.01); **H01L 29/1025** (2013.01); **H01L 29/84** (2013.01); **H01L 29/1054** (2013.01)

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See application file for complete search history.

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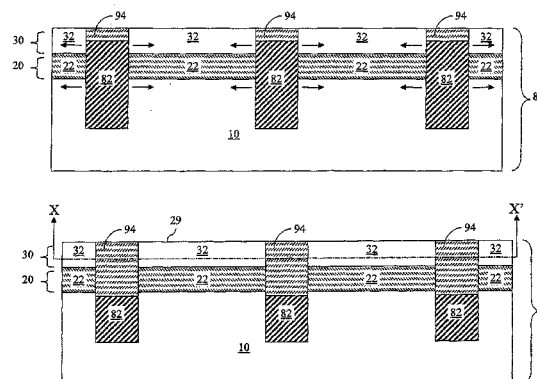
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(57) **ABSTRACT**

A stack pad layers including a first pad oxide layer, a pad nitride layer, and a second pad oxide layer are formed on a semiconductor-on-insulator (SOI) substrate. A deep trench extending below a top surface or a bottom surface of a buried insulator layer of the SOI substrate and enclosing at least one top semiconductor region is formed by lithographic methods and etching. A stress-generating insulator material is deposited in the deep trench and recessed below a top surface of the SOI substrate to form a stress-generating buried insulator plug in the deep trench. A silicon oxide material is deposited in the deep trench, planarized, and recessed. The stack of pad layer is removed to expose substantially coplanar top surfaces of the top semiconductor layer and of silicon oxide plugs. The stress-generating buried insulator plug encloses, and generates a stress to, the at least one top semiconductor region.

**14 Claims, 19 Drawing Sheets**



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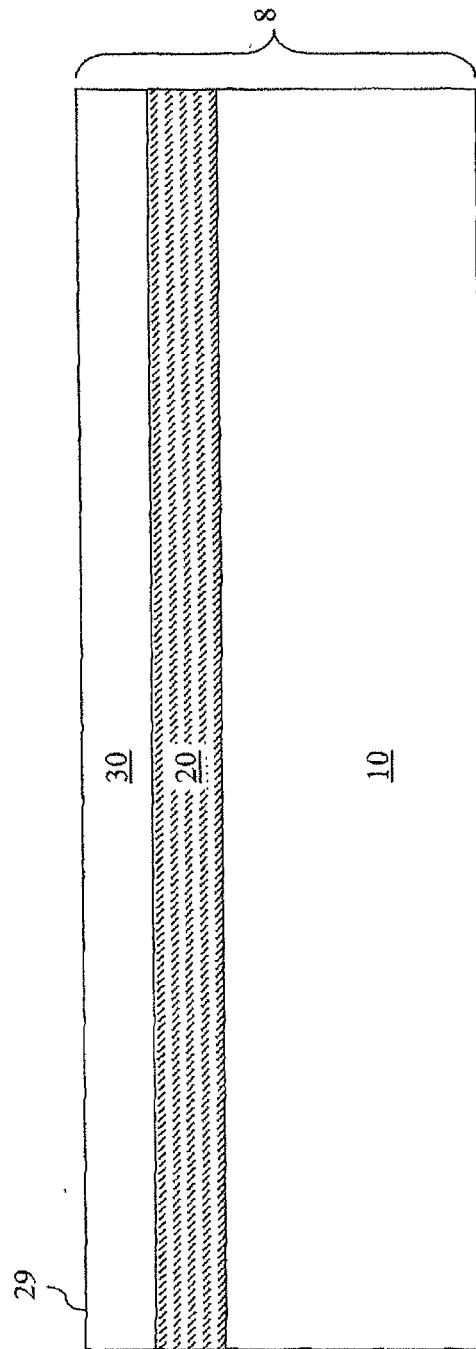


FIG. 1

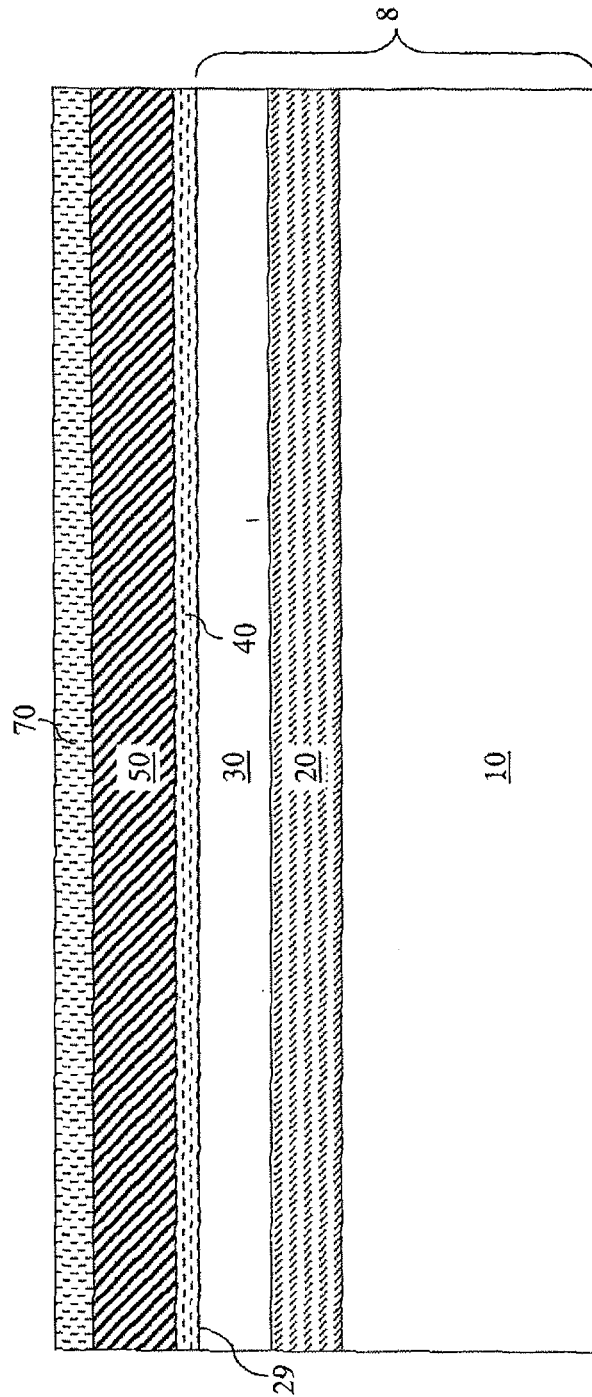


FIG. 2

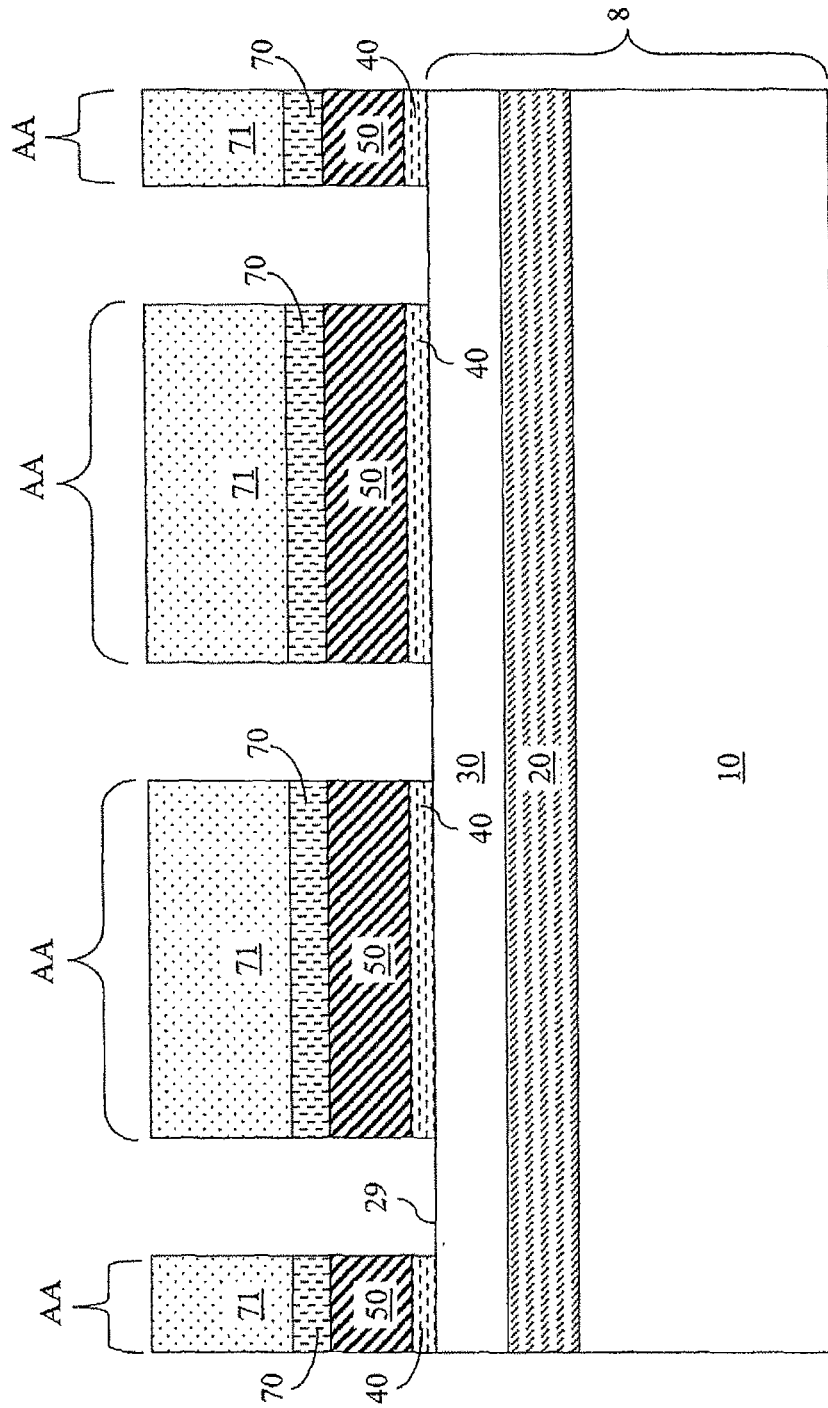


FIG. 3

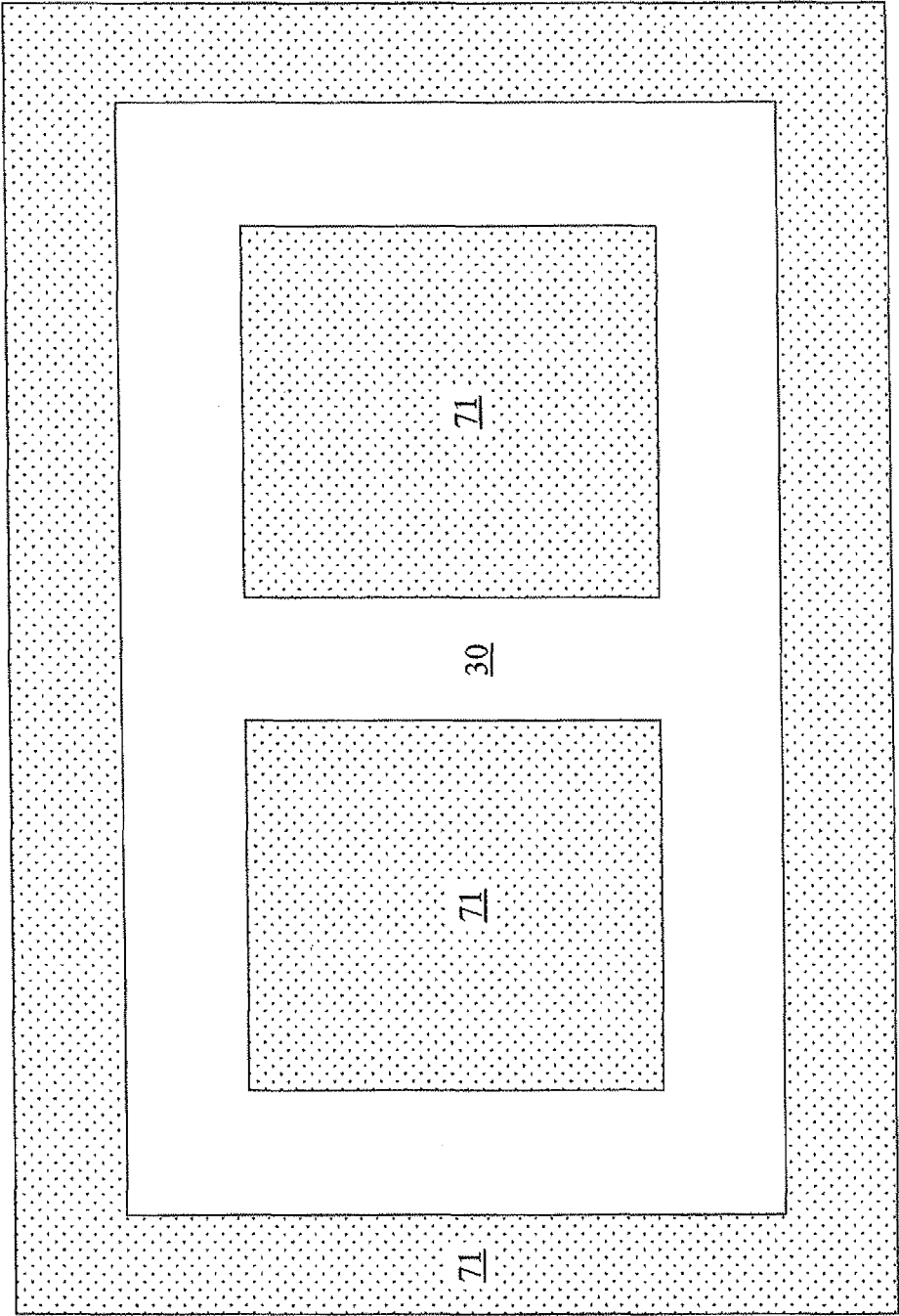


FIG. 4

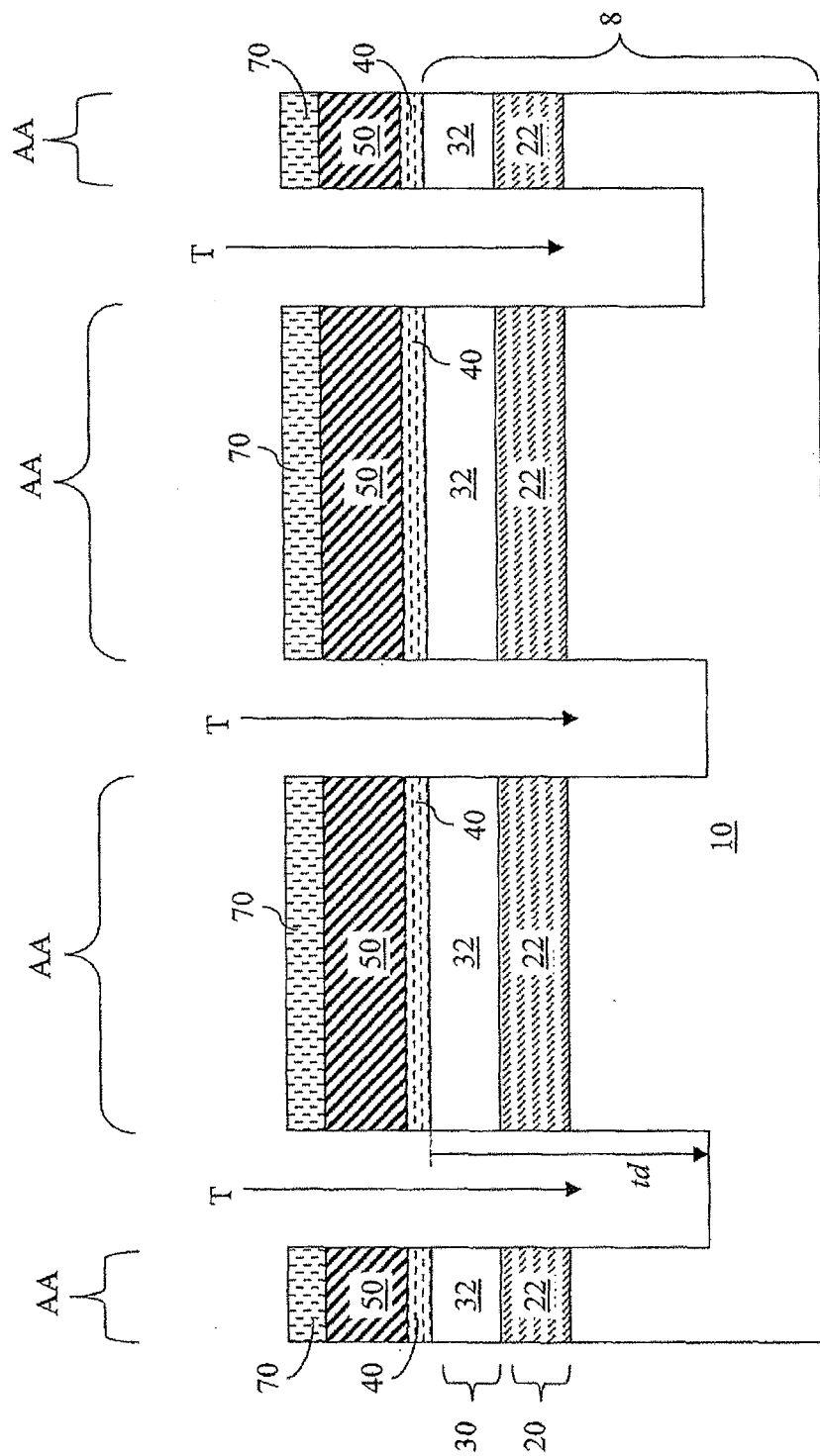


FIG. 5



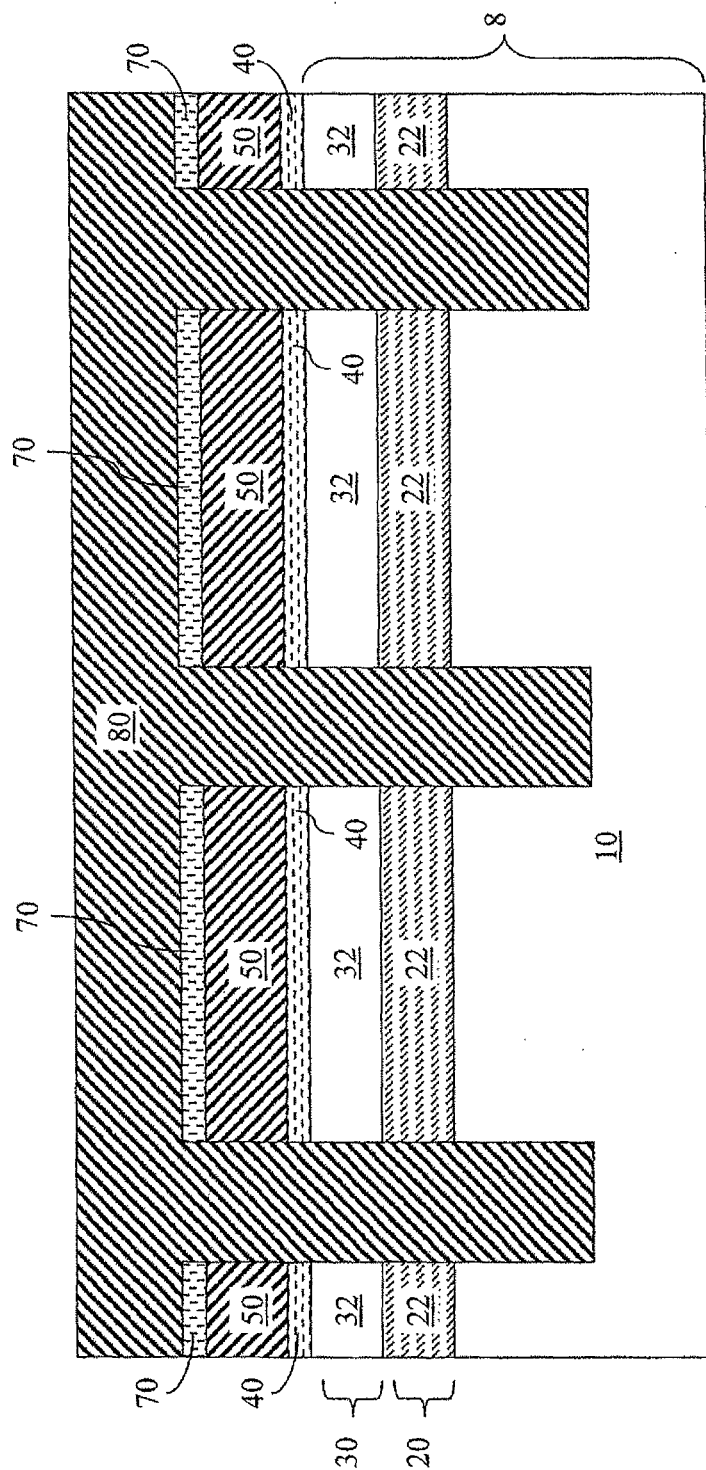


FIG. 6

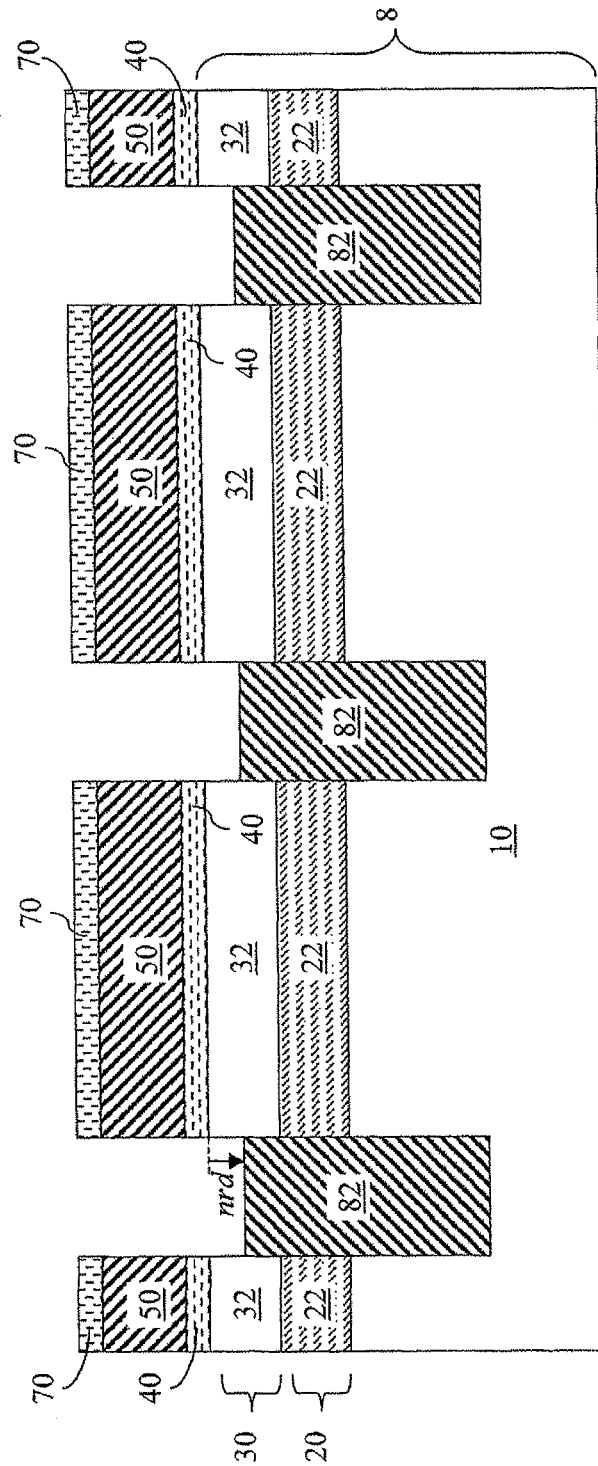


FIG. 7

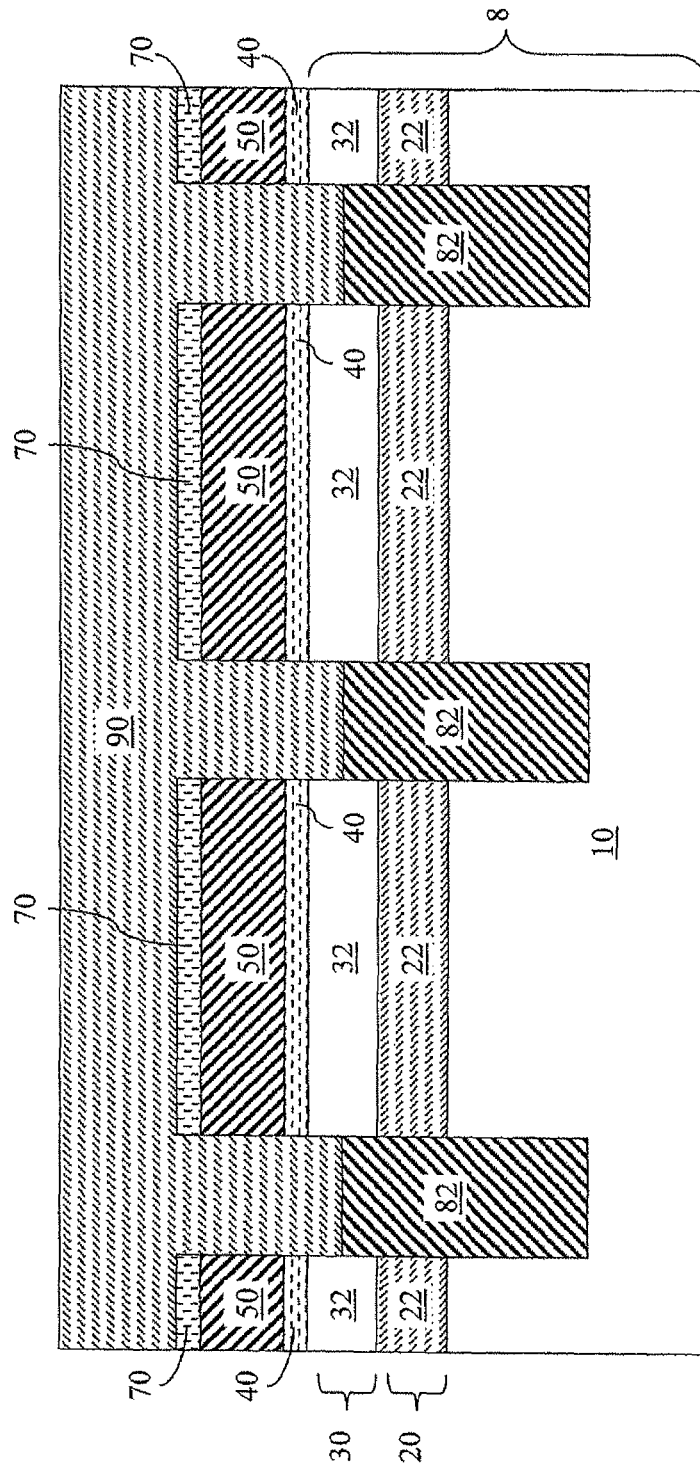


FIG. 8

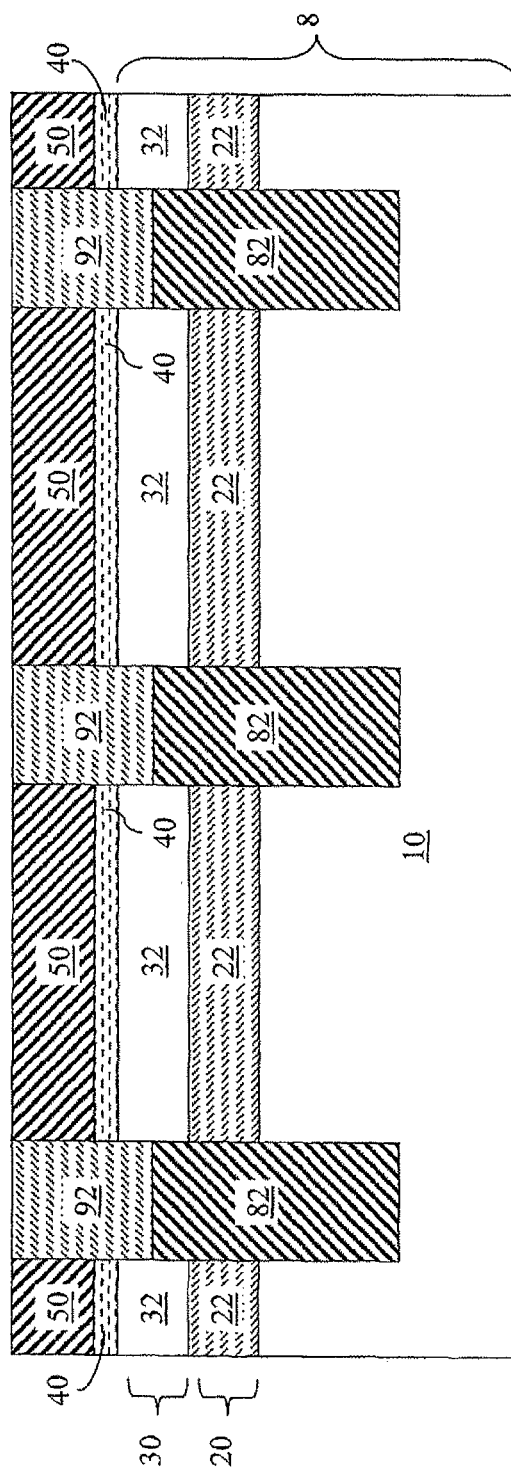


FIG. 9

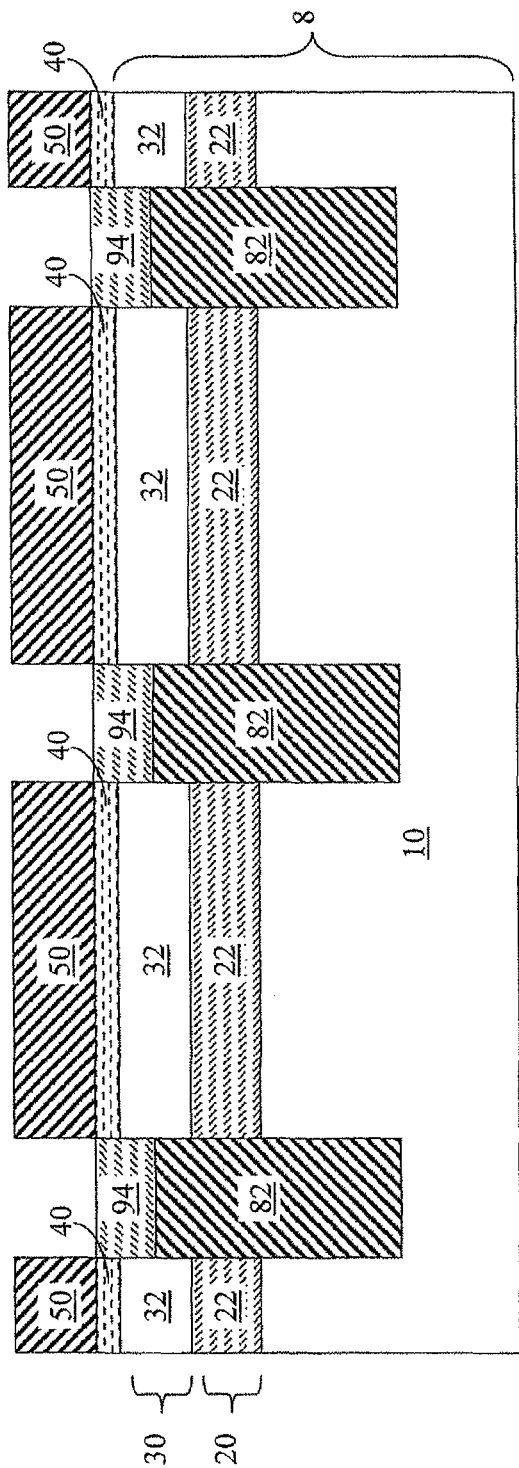


FIG. 10

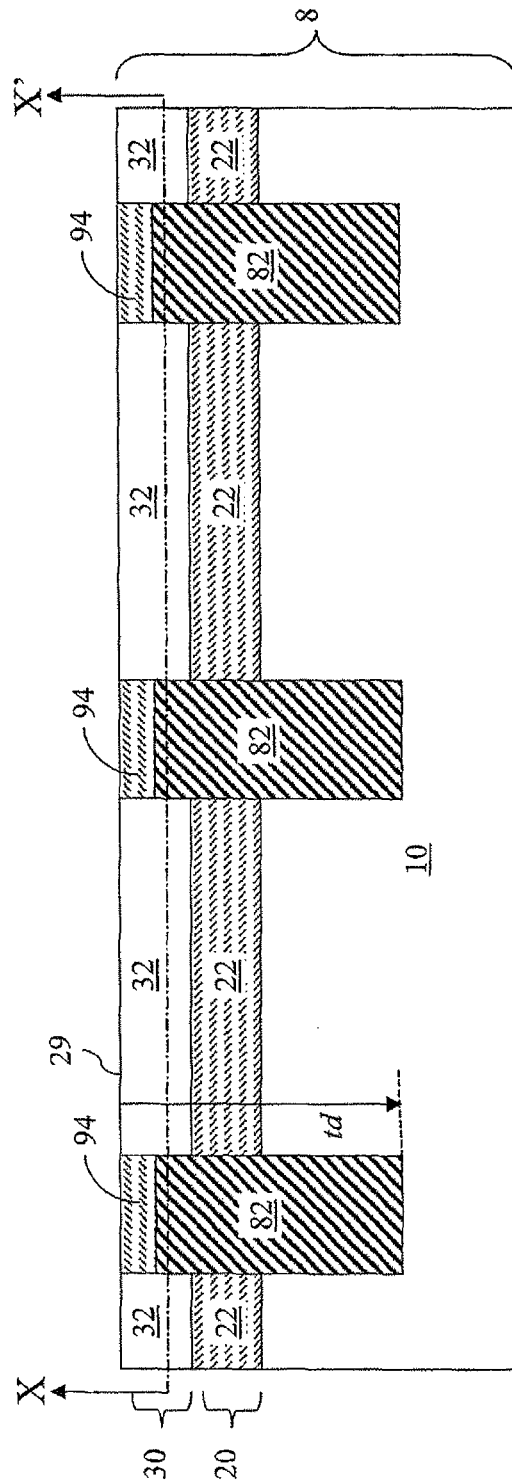


FIG. 11

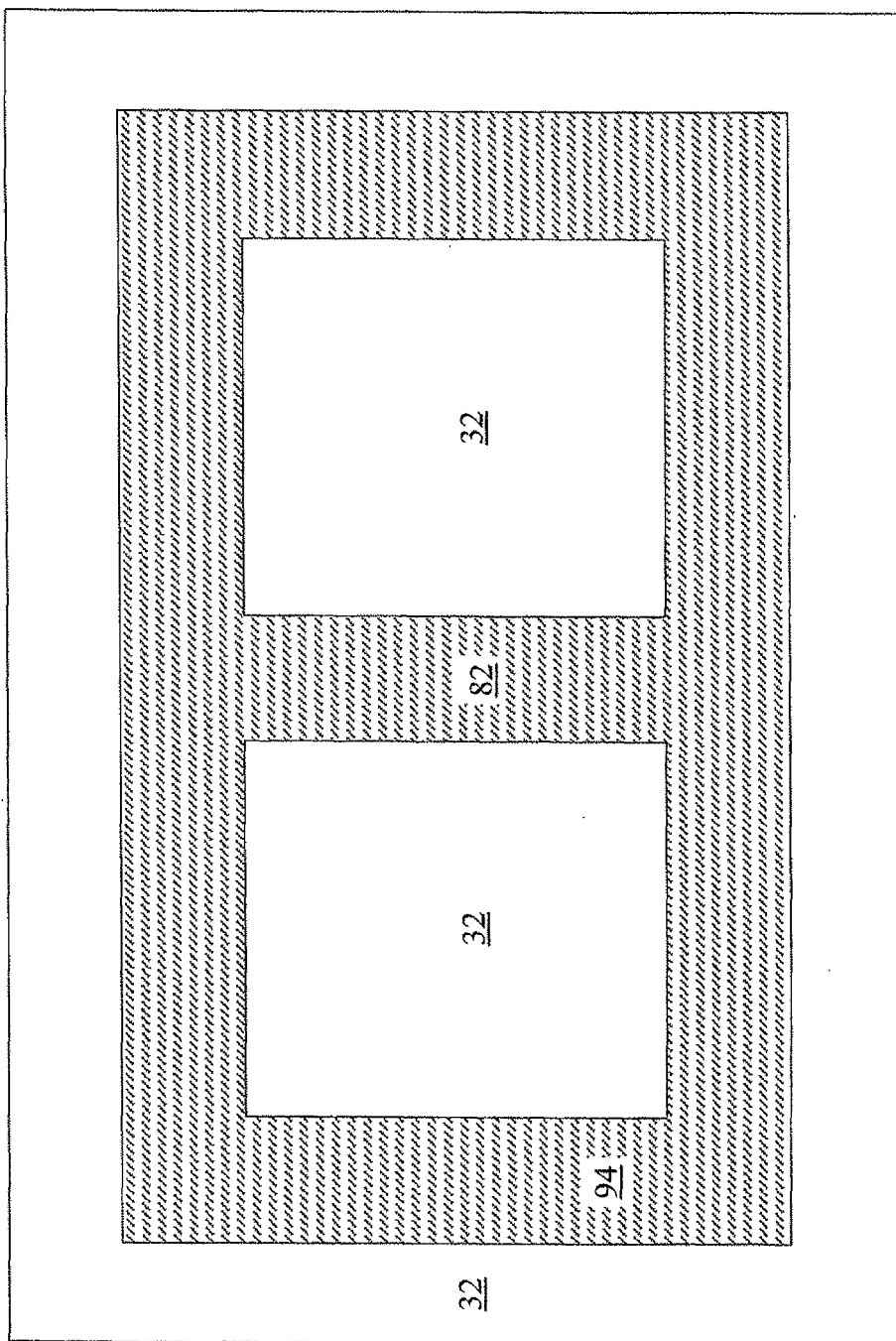


FIG. 12

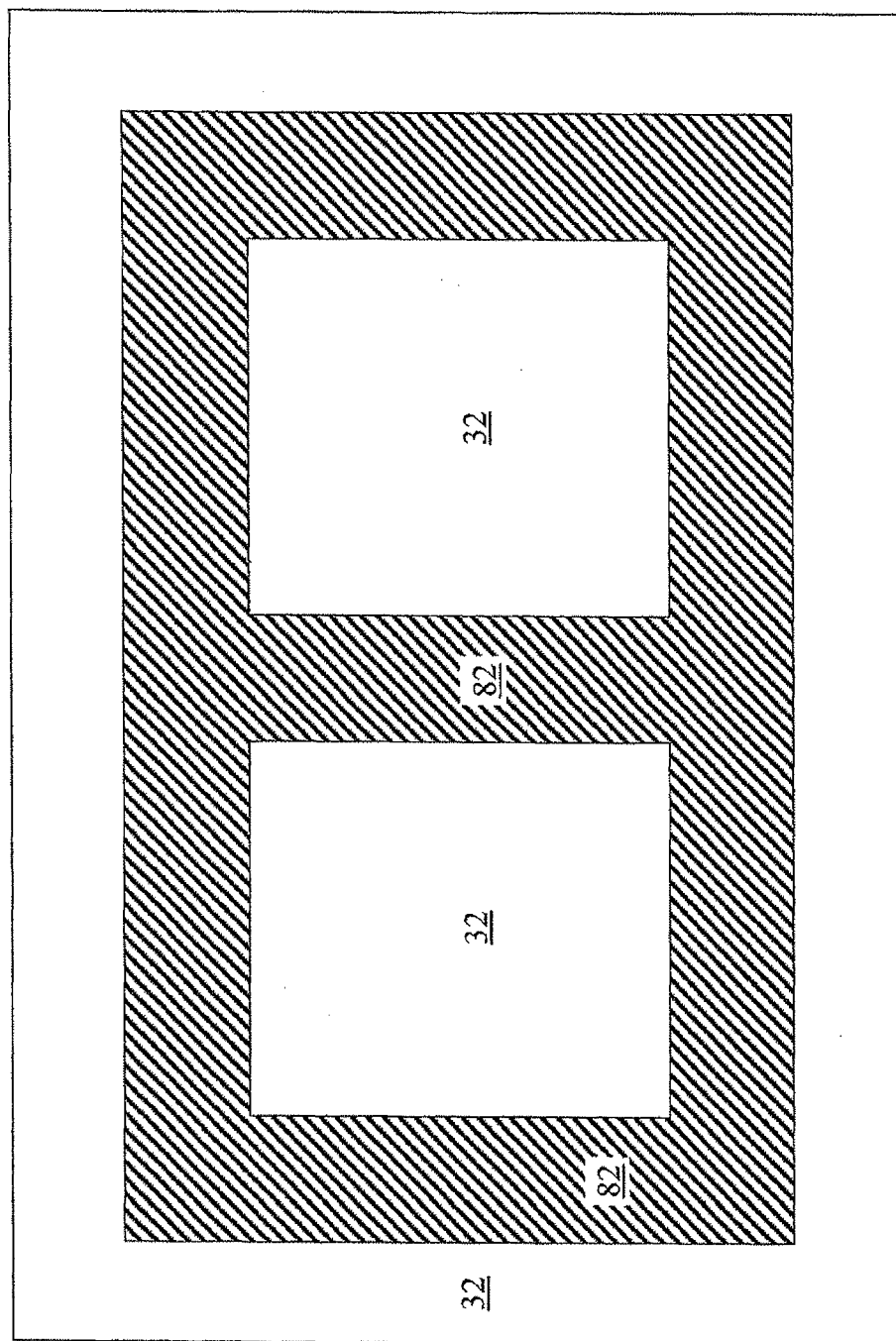


FIG. 13



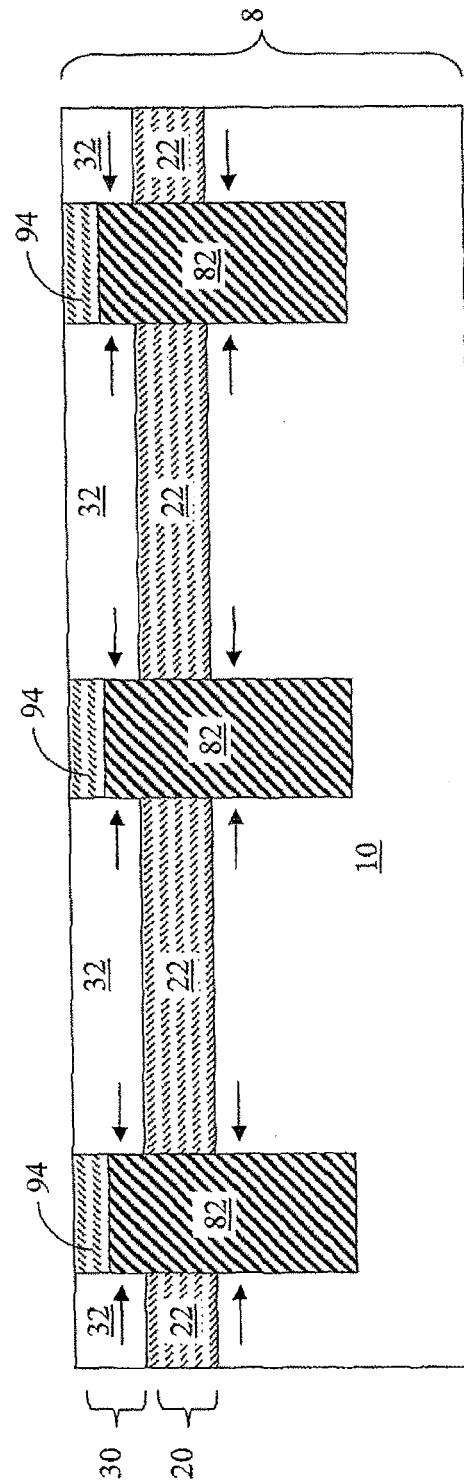


FIG. 14

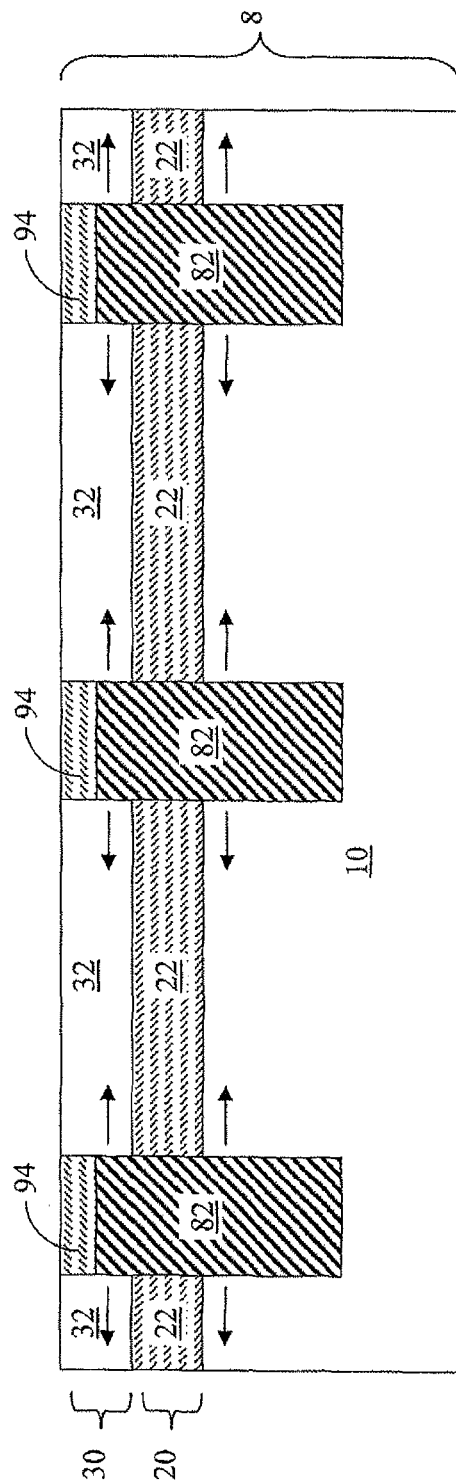


FIG. 15

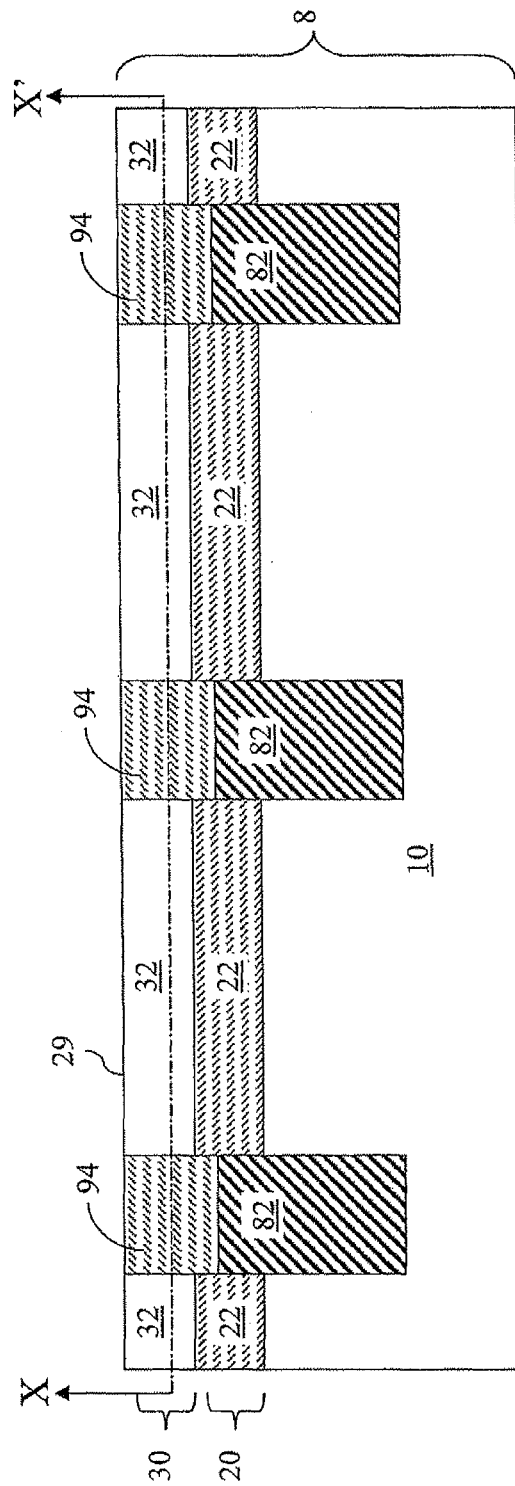


FIG. 16

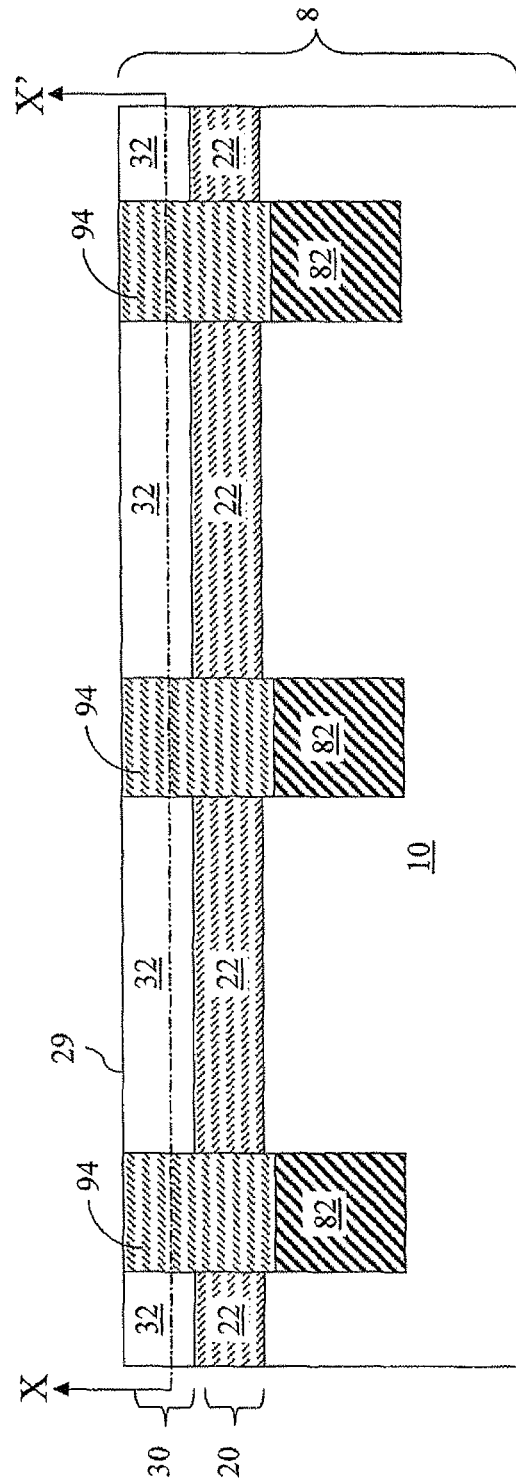


FIG. 17

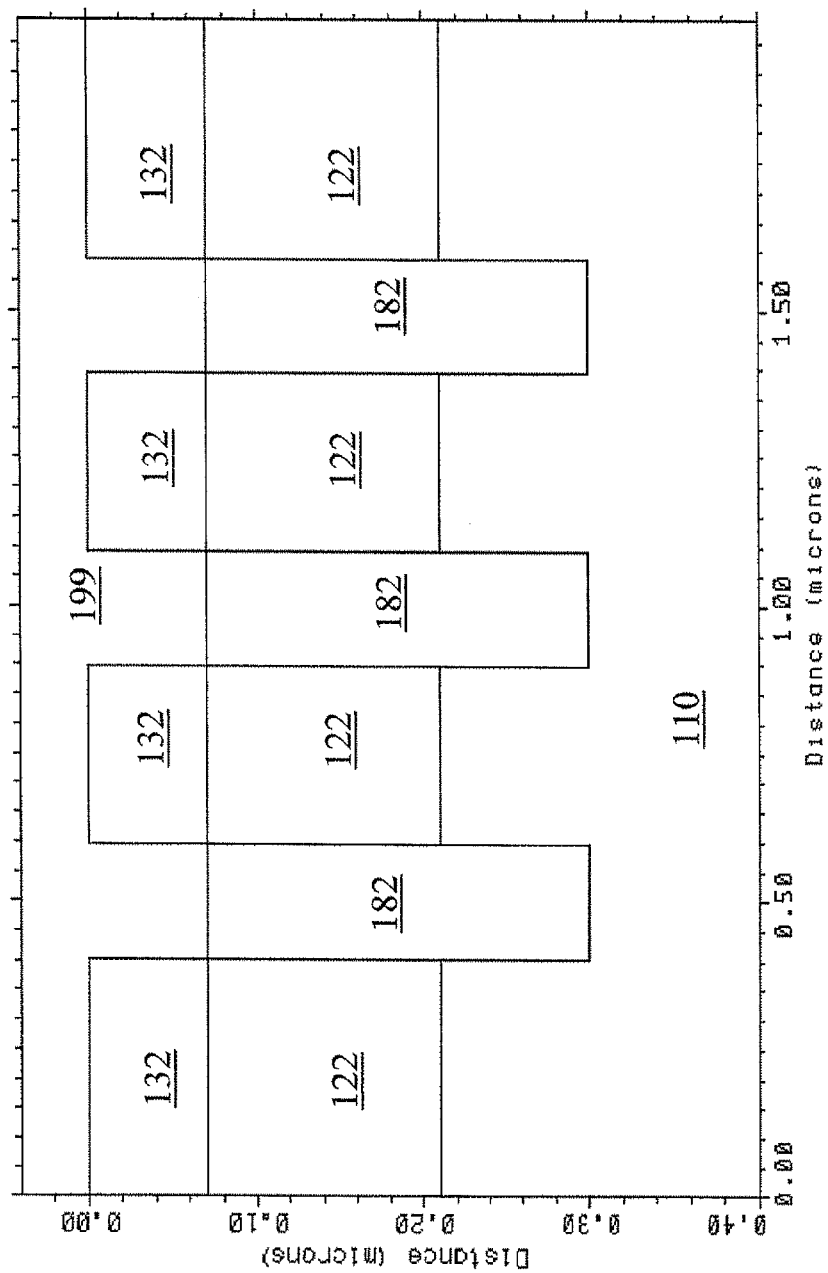


FIG. 18

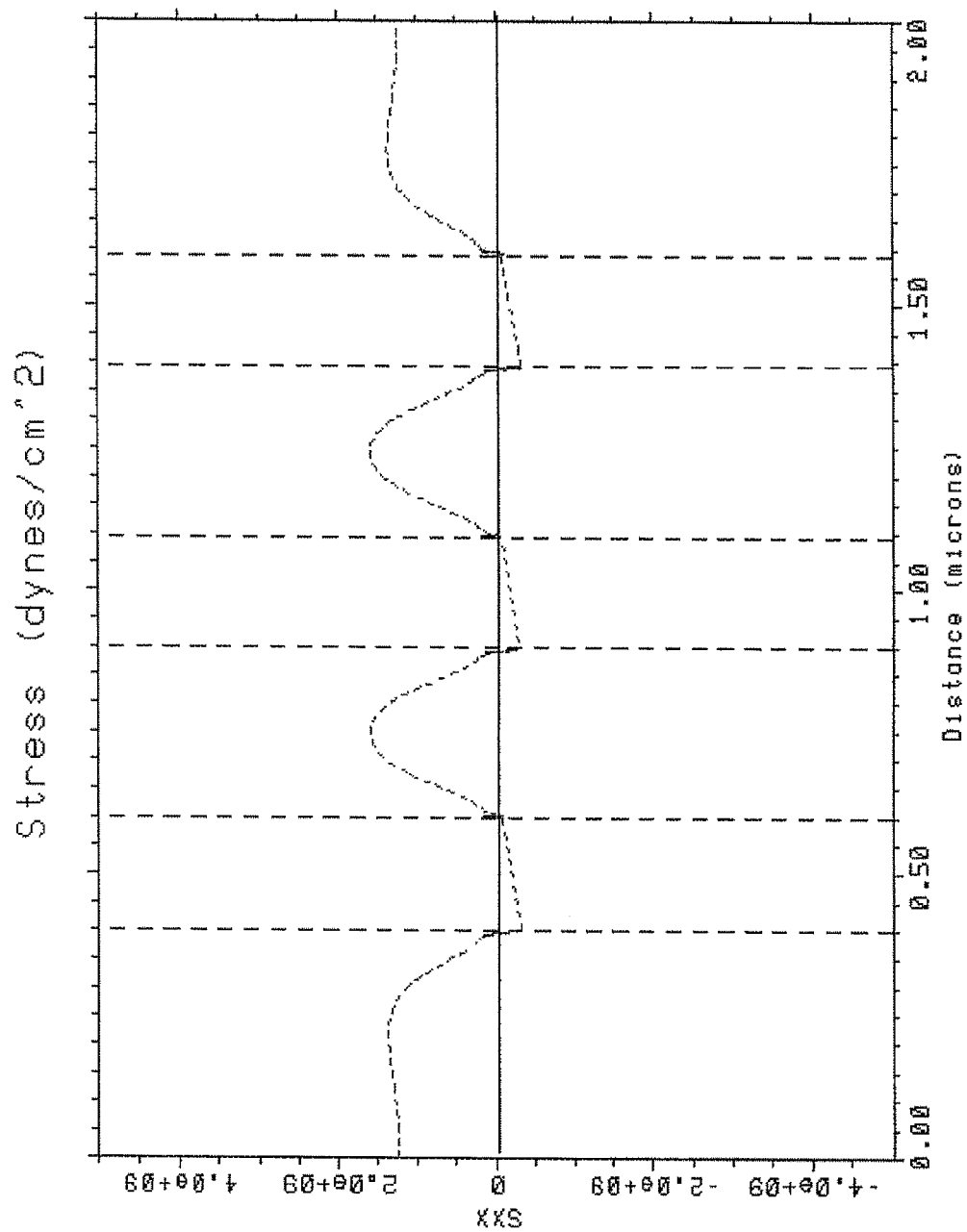


FIG. 19

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## STRESS-GENERATING STRUCTURE FOR SEMICONDUCTOR-ON-INSULATOR DEVICES

This application is a divisional application of U.S. Ser. No. 13/370,898 filed on Feb. 10, 2012 which is a divisional application of U.S. Ser. No. 11/860,851, filed on Sep. 25, 2007. The entire contents of each of the aforementioned U.S. application are incorporated herein by reference.

### FIELD OF THE INVENTION

The present invention generally relates to semiconductor structures, and particularly to stress-generating structures for semiconductor-on-insulator (SOI) devices and methods of manufacturing the same.

### BACKGROUND OF THE INVENTION

When stress is applied to the channel within an active area of a semiconductor transistor, the mobility of carriers, and as a consequence, the transconductance and the on-current of the transistor are altered from their corresponding values for a transistor containing an unstressed semiconductor. This is because the applied stress and the resulting strain on the semiconductor structure within the channel affects the band gap structure (i.e., breaks the degeneracy of the band structure) and changes the effective mass of carriers. The effect of the stress depends on the crystallographic orientation of the plane of the channel, the direction of the channel within the crystallographic orientation, the direction of the applied stress, and the type of carriers.

The effect of stress on the performance of semiconductor devices, especially on the performance of a metal-oxide-semiconductor field effect transistor (MOSFET, or a "FET" in short) device built on a silicon substrate, has been extensively studied in the semiconductor industry. For a p-type MOSFET (PMOSFET, or a "PFET" in short) utilizing a silicon channel, the mobility of minority carriers in the channel (which are holes in this case) increases under uniaxial compressive stress along the direction of the channel, i.e., the direction of the movement of holes or the direction connecting the drain to the source. Conversely, for an n-type MOSFET (NMOSFET, or an "NFET" in short) devices utilizing a silicon channel, the mobility of minority carriers in the channel (which are electrons in this case) increases under uniaxial tensile stress along the direction of the channel, i.e., the direction of the movement of electrons or the direction connecting the drain to the source. Tensile stress in transverse direction, i.e., the direction perpendicular to the movement of carriers, can enhance both electron and hole mobilities. Thus, performance of field effect transistors may be improved by forming a stress-generating structure in or on a semiconductor substrate.

Methods of employing stress-generating shallow trench isolation liners in a bulk substrate are known in the art. Direct application of such methods to semiconductor-on-insulator substrate results in an insignificant amount of improvement in performance compared to bulk equivalents. This is because the thickness of a top semiconductor layer is much less than a depth of shallow trench isolation in bulk substrates, which may be from about 300 nm to about 450 nm, and the amount of stress transferred to SOI devices is proportional to the thickness of the top semiconductor layer, which may be from about 5 nm to about 30 nm in the case of ultra-thin semiconductor-on-insulator (UTSOI) substrates employed for high performance devices.

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In view of the above, there exists a need for an effective stress-generating structure for semiconductor-on-insulator (SOI) devices, and methods of manufacturing the same.

Further, current semiconductor processing sequence used in industry employs silicon oxide as a trench fill material. Modification of an exposed structure of the trench isolation structure would require alterations to subsequent processing steps.

Therefore, there exists a need for an effective stress-generating structure that is compatible with existing semiconductor processing after formation of trench isolation structures, and methods of manufacturing the same.

### SUMMARY OF THE INVENTION

The present invention addresses the needs described above by providing a stress-generating structure which is compatible with semiconductor-on-insulator substrates and existing processing after formation of trench isolation structures, and methods of manufacturing the same.

In the present invention, a stack of pad layers including a first pad oxide layer, a pad nitride layer, and a second pad oxide layer are formed on a semiconductor-on-insulator (SOI) substrate. A deep trench extending below a bottom surface of a buried insulator layer of the SOI substrate and enclosing at least one top semiconductor region is formed by lithographic methods and etching. A stress-generating nitride material is deposited in the deep trench and recessed below a top surface of the SOI substrate to form a stress-generating buried nitride plug in the deep trench. A silicon oxide material is deposited in the deep trench, planarized, and recessed. The stack of pad layers is removed to expose substantially coplanar top surfaces of the top semiconductor layer and of silicon oxide plugs. The stress-generating buried nitride plug encloses, and generates either a compressive stress or tensile stress to, the at least one top semiconductor region.

According to an aspect of the present invention, a semiconductor structure is provided which comprises:

a semiconductor-on-insulator (SOI) substrate including a handle substrate, at least one buried insulator portion abutting the handle substrate, and at least one top semiconductor portion abutting the at least one buried insulator portion;

a trench extending from a top surface of the at least one top semiconductor portion to a depth below a top surface of the at least one buried insulator portion; and

a stack of an insulator stressor plug and a silicon oxide plug located in the trench, wherein the insulator stressor plug abuts a bottom surface of the trench and the silicon oxide plug is substantially coplanar with the top surface of the at least one top semiconductor portion.

In one embodiment, the trench extends a depth below a bottom surface of the at least one buried insulator portion.

In another embodiment, the insulator stressor plug comprises a silicon nitride and applies a tensile stress or a compressive stress to the at least one top semiconductor portion.

In even another embodiment, a magnitude of the tensile stress or the compressive stress is greater than 0.2 GPa in a region in the at least one top semiconductor portion.

In yet another embodiment, the insulator stressor plug laterally abuts, and encloses, the at least one buried insulator portion.

In still another embodiment, the insulator stressor plug laterally abuts and encloses the at least one top semiconductor portion.

In still yet another embodiment, an interface between the insulator stressor plug and the silicon oxide plug is located between the top surface of the at least one top semiconductor

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portion and a bottom surface of the at least one top semiconductor portion, or at the bottom surface of the at least one top semiconductor portion.

In a further embodiment, an interface between the insulator stressor plug and the silicon oxide plug is located between a top surface of the at least one buried insulator portion and the bottom surface of the at least one buried insulator portion, or at the bottom surface of the at least one buried insulator portion.

In an even further embodiment, an interface between the insulator stressor plug and the silicon oxide plug is located beneath the bottom surface of the at least one buried insulator portion.

In a yet further embodiment, the at least one top semiconductor layer comprises one of silicon, germanium, a silicon germanium alloy, a silicon carbon alloy, and a silicon germanium carbon alloy.

In a still further embodiment, a thickness of the at least one top semiconductor portion is from about 5 nm to about 300 nm, and wherein a depth of the trench is from about 200 nm to about 8,000 nm.

According to another aspect of the present invention, a method of forming a semiconductor structure is provided, which comprises:

forming a trench extending from a top surface of a semiconductor-on-insulator (SOI) substrate to a depth beneath a bottom surface of a buried insulator layer of the SOI substrate; and

forming a stack of an insulator stressor plug and a silicon oxide plug in the trench, wherein the insulator stressor plug abuts a bottom surface of the trench, and wherein the silicon oxide plug is substantially coplanar with a top surface of at least one top semiconductor portion formed in a top semiconductor layer of the SOI substrate.

In one embodiment, the method further comprises:

forming a stack of pad layers directly on the SOI substrate; applying a photoresist on the stack of pad layers and lithographically patterning the photoresist; and

transferring a pattern in the resist into the stack of pad layers and the SOI substrate by at least one reactive etch.

In another embodiment, the trench laterally abuts and encloses the at least one top semiconductor portion and at least one buried insulator portion, wherein the at least one buried insulator portion vertically abuts the at least one top semiconductor portion.

In yet another embodiment, the method further comprises:

depositing a silicon nitride into the trench; and

recessing the silicon nitride in the trench to form the insulator stressor plug.

In still another embodiment, the insulator stressor plug comprises a silicon nitride and applies a compressive stress or a tensile stress to the at least one top semiconductor portion.

In still yet another embodiment, a magnitude of the tensile stress or the compressive stress exceeds 0.2 GPa in a region in the at least one top semiconductor portion.

In a further embodiment, the method further comprises:

depositing a silicon oxide into the trench on top of the insulator stressor plug; and

recessing the silicon oxide in the trench to form the silicon oxide plug.

In an even further embodiment, an interface between the insulator stressor plug and the silicon oxide plug is located between the top surface of the at least one top semiconductor portion and a bottom surface of the at least one top semiconductor portion, or at the bottom surface of the at least one top semiconductor portion.

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In a yet further embodiment, an interface between the insulator stressor plug and the silicon oxide plug is located between a top surface of the buried insulator layer and the bottom surface of the buried insulator layer, or at the bottom surface of the buried insulator layer.

In a still further embodiment, a thickness of the at least one top semiconductor portion is from about 5 nm to about 300 nm, and wherein a depth of the trench is from about 200 nm to about 8,000 nm.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1-3, 5-11 are sequential vertical cross-sectional views of a first exemplary semiconductor structure according to the present invention.

FIG. 4 is a top-down view of the exemplary semiconductor structure in FIG. 4.

FIG. 12 is a top-down view of the exemplary semiconductor structure in FIG. 11.

FIG. 13 is a horizontal cross-sectional view of the exemplary semiconductor structure in FIG. 11 along the plane X-X'.

Each of FIGS. 14-15 is a superposition of FIG. 11 with a stress schematic indicating the direction of stress generated by a stress-generating nitride plug.

FIG. 16 is a vertical cross-sectional view of a second exemplary semiconductor structure according to the present invention.

FIG. 17 is a vertical cross-sectional view of a third exemplary semiconductor structure according to the present invention.

FIG. 18 is a two-dimensional model for simulation of stress in a fourth exemplary semiconductor structure according to the present invention.

FIG. 19 is a plot of lateral stress from a simulation employing the two-dimensional model of FIG. 15.

#### DETAILED DESCRIPTION OF THE INVENTION

As stated above, the present invention relates to particularly to stress-generating structures for semiconductor-on-insulator (SOI) devices and methods of manufacturing the same, which are now described in detail with accompanying figures. It is noted that like and corresponding elements are referred to by like reference numerals.

Referring to FIG. 1, a vertical cross-sectional view of a first exemplary semiconductor structure is shown, which comprises a semiconductor-on-insulator (SOI) substrate 8 containing a handle substrate 10, a buried insulator layer 20, and a top semiconductor layer 30. The handle substrate 10 may comprise a semiconductor material such as silicon. Preferably, the handle substrate 10 comprises a single crystalline semiconductor material. The handle substrate 10 may have a p-type doping or an n-type doping. The conductivity of the doping of the handle substrate 10 is herein referred to as a first conductivity type. The dopant concentration of the handle substrate 10 is from about  $1.0 \times 10^{14}/\text{cm}^3$  to about  $3.0 \times 10^{17}/\text{cm}^3$ , and typically at a dopant concentration from about  $1.0 \times 10^{15}/\text{cm}^3$  to about  $3.0 \times 10^{16}/\text{cm}^3$ . The buried insulator layer 20 comprises a dielectric material such as a silicon oxide or a silicon nitride. Preferably, the buried insulator layer 20 comprises thermal silicon oxide. The thickness of the buried insulator layer 20 may be from about 50 nm to about 400 nm, and typically from about 100 nm to about 200 nm. Implementation of the present invention on a hybrid substrate containing a bulk portion and an SOI portion is explicitly contemplated herein.



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The top semiconductor layer **30** comprises a semiconductor material that may be selected from, but is not limited to, silicon, germanium, silicon-germanium alloy, silicon carbon alloy, silicon-germanium-carbon alloy, gallium arsenide, indium arsenide, indium phosphide, III-V compound semiconductor materials, II-VI compound semiconductor materials, organic semiconductor materials, and other compound semiconductor materials. The thickness of the top semiconductor layer **30** may be from about 5 nm to about 300 nm, and preferably from about 5 nm to about 100 nm. Preferably, the entirety of the top semiconductor layer **30** comprises a single crystalline semiconductor material.

The top semiconductor layer **30** may have a built-in biaxial stress in the plane of the top semiconductor layer **30**, i.e., in the plane perpendicular to the direction of the surface normal of a substrate top surface **29**, which is a top surface of the SOI substrate **8**. The top semiconductor layer **30** may be substantially undoped or may have a doping of the first conductivity type or a doping of the opposite type of the first conductivity type, which is herein referred to as a second conductivity type. The dopant concentration of the top semiconductor layer **30** may be from about  $1.0 \times 10^{14}/\text{cm}^3$  to about  $3.0 \times 10^{17}/\text{cm}^3$ , and typically from about  $1.0 \times 10^{15}/\text{cm}^3$  to about  $3.0 \times 10^{16}/\text{cm}^3$ , although lesser and greater dopant concentrations are explicitly contemplated herein.

Referring to FIG. 2, a stack of pad layers is formed on the substrate top surface **29**. Specifically, a first pad oxide layer **40** is formed directly on the substrate top surface. The first pad oxide layer **40** may comprise a thermal oxide of the semiconductor material in the top semiconductor layer **30**, or may comprise a dielectric oxide material deposited by chemical vapor deposition (CVD). The first pad oxide layer **40** may comprise a silicon oxide such as a thermal silicon oxide or a deposited silicon oxide formed by CVD. The thickness of the first pad layer **40** is from about 3 nm to about 30 nm, and typically from about 5 nm to about 15 nm.

A pad nitride layer **50** is deposited on the first pad layer **40**, for example, by chemical vapor deposition such as low pressure chemical vapor deposition (LPCVD) or rapid thermal chemical vapor deposition (RTCVD). The pad nitride layer **50** may comprise silicon nitride, or other dielectric nitride having sufficient resistance to chemical mechanical polishing. The thickness of the pad nitride layer **50** may be from about 50 nm to about 250 nm, and typically from about 10 nm to about 20 nm.

A second pad oxide layer **70** is formed on the pad nitride layer **50**, for example, by chemical vapor deposition such as low pressure chemical vapor deposition (LPCVD), rapid thermal chemical vapor deposition (RTCVD), or high density plasma chemical vapor deposition (HDPCVD). The second pad oxide layer **70** may comprise silicon oxide or other semiconductor oxide providing sufficient resistance to etching during a subsequent etching of silicon nitride.

The thickness of the second pad oxide layer **70** may be from about 10 nm to about 1,000 nm. The thickness of the second oxide layer **70** depends on a target depth of a trench into the SOI substrate **8** and the nature of etching process employed to form the trench. For example, in case the depth of the trench to be formed, as measured from the substrate top surface to a bottom of the trench, is from about 200 nm to about 500 nm, and a soft mask process, in which the photoresist **71** is present throughout the etching process, the thickness of the second pad oxide layer may be from about 10 nm to about 100 nm. In case the depth of the trench to be formed is from about 500 nm to about 8,000 nm, and a hard mask

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as patterned is employed as an etch mask, the thickness of the second pad oxide layer may be from about 50 nm to about 1,000 nm.

Referring to FIGS. 3 and 4, a photoresist **71** is applied onto the top surface of the second pad layer and is lithographically patterned to define active areas AA, within which semiconductor devices are subsequently formed. FIG. 3 is a vertical cross-sectional view and FIG. 4 is a top down view of the first exemplary semiconductor structure. The active areas AA correspond to areas in which the photoresist **71** remains after patterning. Typically, each of the active areas AA is disjoined from other active areas, i.e., an area devoid of the photoresist **71** encloses each of the active areas AA. The complement of the set of all active areas AA, i.e., the area without the photoresist **71**, may be a single contiguous area, or may be multiple disjoined areas.

A reactive ion etch is employed to transfer the pattern in the photoresist **71** into the stack of the second pad oxide layer **70**, the pad nitride layer **50**, and the first pad oxide layer **40**, exposing the substrate top surface **29** between the active areas AA. The photoresist **71** may, or may not, be removed at this point depending on the depth of the trench to be subsequently formed and the etch chemistry to be employed therein.

Referring to FIG. 5, the pattern in the photoresist **71** or in the second pad oxide layer **70** is transferred into the SOI substrate **8** by a reactive ion etch to a trench depth *td* from the substrate top surface **29** into the SOI substrate **8**. The trench depth *td* is greater than the depth of a bottom surface of the buried insulator layer **20** as measured from the substrate top surface **29**. The trench depth *td* may be from about 200 nm to about 8,000 nm. In case the complement of the set of all active areas AA is a single contiguous area, a single trench **T** is formed. In case the complement of the set of all active areas AA comprises multiple disjoined areas, a plurality of disjoined trenches is formed. Construction of a plurality of disjoined trenches requires modification of the pattern in the photoresist **71**, which is known to one of ordinary skill in the art.

At least one top semiconductor portion **32** enclosed by the trench **T** is formed from remaining portions of the top semiconductor layer **30**. The collection of all of the at least one top semiconductor portion **32** constitutes the top semiconductor layer **30**. At least one buried insulator portion **22** enclosed by the trench **T** is formed from remaining portions of the buried insulator layer **20**. The collection of all of the at least one buried insulator layer **22** constitutes the buried insulator layer **20**. Each of the at least one top semiconductor portion **32** vertically abuts one of the at least one buried insulator portion **22**. The sidewalls of each of the at least one top semiconductor portion **32** and sidewalls of the buried insulator portion **22** directly underneath are vertically coincident, i.e., coincident in a vertical view such as a top-down view.

Referring to FIG. 6, a silicon nitride layer **80** is deposited in the trench **T** (See FIG. 5) and on the second pad oxide layer **70**. The trench **T** is filled with the silicon nitride layer **80**. Preferably, the silicon nitride layer **80** comprises a stress-generating silicon nitride, which may be the same material as stress-generating silicon nitride liners formed over a gate electrode as known in the art. Such stress-generating silicon nitride liners of the prior art, having a typical thickness from about 30 nm to about 80 nm, are known to generate compressive stress or tensile stress, of which the magnitude may exceed 0.2 GPa. The difference between the prior art and the present invention is that such stress-generating silicon nitride is formed above a top surface of a semiconductor substrate over a gate electrode in the prior art, while the stress-gener-

ating silicon nitride is located in a trench formed beneath the substrate top surface **29** prior to formation of any gate electrode.

As such, the stress-generating silicon nitride may be a tensile stress-generating silicon nitride or a compressive stress-generating silicon nitride. The portion of the silicon nitride layer **80** within the trench **T** exerts a compressive stress or a tensile stress to structures that the trench **T** encloses, which include the at least one top semiconductor portion **32**, the at least one buried insulator portion **22**, and the portion of the handle substrate **10** between a bottom surface of the buried insulator layer **20** and a bottom surface of the trench **T**. The magnitude of the compressive stress or the tensile stress may be greater than 0.2 GPa in a region of each of the at least one top semiconductor portion **32**. In practice, the region in which the magnitude of the compressive stress or the tensile stress exceeds 0.2 GPa may include most of each of the at least one top semiconductor portion **32** except for a boundary region of each of the at least one top semiconductor portion **32** directly on the trench **T**.

The thickness of the silicon nitride layer **80**, as measured above the second pad oxide layer **70**, is greater than half of the narrowest distance in the opening of the trench **T** to insure complete fill of the trench. Consequently, the thickness of the silicon nitride layer is greater than half of the critical dimension, i.e., the minimum dimension that lithographic tools may print. The critical dimension is reduced with each generation of lithographic tools, and is about 50 nm as of 2007. The thickness of the silicon nitride layer **80** may be from about 25 nm to about 300 nm, and preferably from about 25 nm to about 150 nm, although lesser and greater thicknesses are also explicitly contemplated herein.

The stress-generating silicon nitride employed for the silicon nitride layer **80** may be formed by chemical vapor deposition (CVD) such as plasma enhanced chemical vapor deposition (PECVD), high density plasma chemical vapor deposition (HDPCVD), rapid thermal chemical vapor deposition (RTCVD), low pressure chemical vapor deposition (LPCVD), or a combination thereof.

Referring to FIG. 7, the silicon nitride layer **80** (See FIG. 6) is recessed below a top surface of the at least one top semiconductor portion **32**. The depth of recess as measured from the top surface of the at least one top semiconductor portion **32**, which is herein referred to as a nitride recess depth **nrd**, may be less than the thickness of the at least one top semiconductor portion **32** so that the top surface of an insulator stressor plug **82**, which is the remaining portion of the silicon nitride layer **80**, is located between the top surface of the at least one top semiconductor portion **32** and a bottom surface of the at least one top semiconductor portion **32**. Alternately, the nitride recess depth **nrd**, may be equal to the thickness of the at least one top semiconductor portion **32** so that the top surface of the insulator stressor plug **82** is at the depth of the bottom surface of the at least one top semiconductor portion **32**. Even alternately, the nitride recess depth **nrd** may be greater than the thickness of the at least one top semiconductor portion **32** and less than the sum of the thickness of the at least one top semiconductor portion **32** and the thickness of the at least one buried insulator portion **22** so that the top surface of an insulator stressor plug **82** is located between a top surface of the at least one buried insulator portion **22** and a bottom surface of the at least one buried insulator portion **22**. Yet alternately, the nitride recess depth **nrd**, may be equal to the sum of the thickness of the at least one top semiconductor portion **32** and the thickness of the at least one buried insulator portion **22** so that the top surface of the insulator stressor plug **82** is at the depth of the bottom surface of the at

least one buried insulator portion **22**. Still alternately, the nitride recess depth **nrd** may be greater than the sum of the thickness of the at least one top semiconductor portion **32** and the thickness of the at least one buried insulator portion **22** so that the top surface of an insulator stressor plug **82** is located beneath the bottom surface of the at least one buried insulator portion **22**.

An etch process that etches the silicon nitride layer **80** selective to the second pad oxide layer **70** is employed. Preferably, the etch process is a reactive ion etch (RIE) process in which the etch ratio between the silicon nitride layer **80** and the second pad oxide layer **70** is high, so that at least a portion of the second pad oxide layer **70** remains at the end of the reactive ion etch.

Referring to FIG. 8, a silicon oxide layer **90** is deposited on the insulator stressor plug **82** in the trench **T** (See FIG. 5) and on the second pad oxide layer **70**. The portion of the trench **T** above the insulator stressor plug **82** is filled with the silicon oxide layer **90**.

The silicon oxide layer **90** may be formed by chemical vapor deposition (CVD) such as plasma enhanced chemical vapor deposition (PECVD), high density plasma chemical vapor deposition (HDPCVD), rapid thermal chemical vapor deposition (RTCVD), low pressure chemical vapor deposition (LPCVD), or a combination thereof. A precursor containing silicon and oxygen, such as tetra-ethyl-ortho-silicate (TEOS) may be employed in the CVD process. The silicon oxide layer **90** may, or may not, comprise the same material as the second pad oxide layer **70**.

The thickness of the silicon oxide layer **90**, as measured above the second pad oxide layer **70**, is greater than half of the narrowest distance in the opening of the trench **T** to insure complete fill of the trench without a void. Consequently, the thickness of the silicon nitride layer is greater than half of the critical dimension. The thickness of the silicon oxide layer **90** may be from about 25 nm to about 300 nm, and preferably from about 25 nm to about 150 nm, although lesser and greater thicknesses are also explicitly contemplated herein.

Referring to FIG. 9, the silicon oxide layer **90** is planarized by chemical mechanical polishing (CMP) employing the pad nitride layer **50** as a stopping layer. Optionally, a recess etch, which may be a reactive ion etch, a wet etch, a chemical downstream etch, or any combination thereof, may be employed in conjunction with the chemical mechanical polishing. Methods of performing a CMP process on a silicon oxide layer employing a nitride layer as the stopping layer are well known in the art. The remaining portion of the silicon oxide layer **90** after the CMP step constitutes a planarized silicon oxide layer **92**. A top surface of the planarized silicon oxide layer **92** is substantially coplanar with a top surface of the pad nitride layer **50**.

Referring to FIG. 10, the planarized silicon oxide layer **92** is recessed by a first etch that etches the planarized silicon oxide layer **92** selective to the pad nitride layer **50**. The first etch may be a wet etch, a reactive ion etch, a chemical dry etch, or any combination thereof. An exemplary wet etch process is a wet etch employing hydrofluoric acid (HF), which selectively etches the planarized silicon oxide layer **92** relative to the pad nitride layer **50**. The remaining portion of the planarized silicon oxide layer **92** after the etch constitutes a silicon oxide plug **94**. Preferably, a top surface of the silicon oxide plug **94** is located about the interface between the first pad oxide layer **40** and the pad nitride layer **50**.

Referring to FIGS. 11-13, the pad nitride layer **50**, the first pad oxide layer **40**, and a top portion of the silicon oxide plug **94** are removed. FIG. 11 is a vertical cross-sectional view of the first exemplary semiconductor structure. FIG. 12 is a

top-down view of the first exemplary semiconductor structure in FIG. 11. FIG. 13 is a horizontal cross-sectional view of the first exemplary semiconductor structure in FIG. 11 along the plane X-X'.

Specifically, the pad nitride layer 50 is removed selective to the silicon oxide plug 94 and the first pad oxide layer 40 by a second etch, which may be a wet etch, a reactive ion etch, a chemical dry etch, or any combination thereof. In case the pad nitride layer 50 comprises silicon nitride, a wet etch employing hot phosphoric acid may be employed to selectively remove the pad nitride layer 50, while not affecting the silicon oxide plug 94 and the first pad oxide layer 40.

The first pad oxide layer 40 and a top portion of the silicon oxide plug 94 may then be removed by a third etch selective to the at least one top semiconductor portion 32. The third etch may be, for example, a wet etch employing hydrofluoric acid (HF). Preferably, amount of removal of the top portion of the silicon oxide plug 94 is such that a top surface of the silicon oxide plug 94 is substantially coplanar with the top surface of the at least one top semiconductor portion 32.

The first exemplary semiconductor structure of FIGS. 11-13 comprises:

a semiconductor-on-insulator (SOI) substrate 8 including a handle substrate 10, at least one buried insulator portion 22 abutting the handle substrate 10, and at least one top semiconductor portion 32 abutting the at least one buried insulator portion 22;

a trench extending from a top surface, which is the substrate top surface 29, of the at least one top semiconductor portion 32, to a depth, which is the trench depth td, below a bottom surface of the at least one buried insulator portion 22; and

a stack of an insulator stressor plug 82 and a silicon oxide plug 94 located in the trench, wherein the insulator stressor plug 82 abuts a bottom surface of the trench and the silicon oxide plug 94 is substantially coplanar with the top surface, which is the substrate top surface 29, of the at least one top semiconductor portion 32.

In the first exemplary semiconductor structure, an interface between the insulator stressor plug 82 and the silicon oxide plug 94 is located between the top surface, which is the substrate top surface 29, of the at least one top semiconductor portion 32 and a bottom surface of the at least one top semiconductor portion 32.

The first exemplary semiconductor structure provides a substantially flat top surface, which is the substrate top surface 29, over the entirety of the SOI substrate 8. Further, the substrate top surface 29 comprises a semiconductor material of the at least one semiconductor portion 32 and silicon oxide of the silicon oxide plug 94. This composition is identical to the composition of a top surface of a conventional complementary metal-oxide-semiconductor (CMOS) structure after formation of shallow trench isolation. Thus, the first exemplary semiconductor structure may employ identical processing steps after the processing step of FIGS. 11-13 as conventional CMOS structures. In other words, the first exemplary semiconductor structure is compatible with conventional semiconductor processing sequence after the step of FIGS. 11-13.

Referring to FIG. 14, a stress schematic indicating the direction of stress generated by the insulator stressor plug 82 is shown in superposition on the first exemplary semiconductor structure of FIG. 11 for the case in which the insulator stressor plug 82 generates a tensile stress. The tensile stress is applied to the handle substrate 10 and to the at least one top semiconductor portion 32. A semiconductor device may be formed in the at least one top semiconductor portion 32 such

that the tensile stress applied to the at least one top semiconductor portion 32 is advantageously utilized to enhance performance of the semiconductor device. For example, the at least one top semiconductor portion 32 may comprise silicon and the semiconductor device may be an n-type field effect transistor having a channel in the direction of the lateral tensile stress and employing electrons as charge carriers. In this case, the mobility of the electrons increases as a result of the lateral tensile stress on the at least one top semiconductor layer 32.

Referring to FIG. 15, a stress schematic indicating the direction of stress generated by the insulator stressor plug 82 is shown in superposition on the first exemplary semiconductor structure of FIG. 11 for the case in which the insulator stressor plug 82 generates a compressive stress. The compressive stress is applied to the handle substrate 10 and to the at least one top semiconductor portion 32. A semiconductor device may be formed in the at least one top semiconductor portion 32 such that the compressive stress applied to the at least one top semiconductor portion 32 is advantageously utilized to enhance performance of the semiconductor device. For example, the at least one top semiconductor portion 32 may comprise silicon and the semiconductor device may be an p-type field effect transistor having a channel in the direction of the lateral compressive stress and employing holes as charge carriers. In this case, the mobility of the holes increases as a result of the lateral compressive stress on the at least one top semiconductor layer 32.

Referring to FIG. 16, a second exemplary semiconductor structure according to the present invention is shown. The interface between the insulator stressor plug 82 and the silicon oxide plug 94 is located between a top surface of the at least one buried insulator portion 22 and the bottom surface of the at least one buried insulator portion 22.

Referring to FIG. 17, a third exemplary semiconductor structure according to the present invention is shown. The interface between the insulator stressor plug 82 and the silicon oxide plug 94 is located beneath the bottom surface of the at least one buried insulator portion 22.

Embodiments in which the interface between the insulator stressor plug 82 and the silicon oxide plug 94 is located at the bottom surface of the at least one top semiconductor portion 32 or at the bottom surface of the at least one buried insulator portion 22 are explicitly contemplated herein.

Referring to FIG. 18, a two-dimensional model for simulation of stress in a fourth exemplary semiconductor structure according to the present invention. In this two-dimensional model, the structure of the fourth exemplary semiconductor in the direction perpendicular to the plane of the model, i.e., the plane of FIG. 18, is assumed to continue indefinitely, i.e., sufficiently long enough not to affect the results of the simulation.

The cross-sectional area of a handle substrate 10 (See FIG. 11) is approximated by a handle substrate area 110. The cross-sectional area of an insulator stressor plug 82 (See FIG. 11) is approximated by an insulator stressor plug area 182. The cross-sectional area of at least one buried insulator portion 22 (See FIG. 11) is approximated by at least one buried insulator portion area 122. The cross-sectional area of at least one top semiconductor portion 32 (See FIG. 11) is approximated by at least one top semiconductor portion area 132. The effect of a silicon oxide plug 94 is assumed to be insignificant, and a void area 199 was introduced in the area of the silicon oxide plug 94. In this two-dimensional model, a top surface of the insulator stressor plug area 182 is located at the bottom surface of the at least one top semiconductor portion area 132.

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The insulator stressor plug area **182** is assumed to have the same property as one of tensile silicon nitride material known in the art.

FIG. **19** is a plot of lateral stress from a simulation employing the two-dimensional model of FIG. **15**. Lateral tensile stress up to about 1.8 GPa is observed in the at least one top semiconductor portion area **132**. In most regions of the at least one top semiconductor portion area **132**, the lateral tensile stress is greater than 0.5 GPa. The magnitude of the lateral tensile stress falls below 0.5 GPa only near the boundary with the insulator stressor plug area **182** (See FIG. **18**). Thus, the magnitude of the tensile stress may be greater than 0.5 GPa in a region in the at least one top semiconductor portion **32** in the exemplary semiconductor structures demonstrated above.

While the present invention has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in forms and details may be made without departing from the spirit and scope of the present invention. It is therefore intended that the present invention not be limited to the exact forms and details described and illustrated, but fall within the scope of the appended claims.

What is claimed is:

1. A method of forming a semiconductor structure comprising:

providing a semiconductor-on-insulator (SOI) substrate including a handle substrate consisting of a single crystalline semiconductor material, a buried insulating layer present on said handle substrate, and a top semiconductor layer present on said buried insulating layer;

forming a trench extending from a top surface of said SOI substrate to a depth beneath a bottom surface of said buried insulating layer of said SOI substrate to physically expose a portion of said handle substrate at a bottom of said trench, wherein said trench laterally abuts and encloses at least one top semiconductor portion formed in said top semiconductor layer of said SOI substrate; and

forming a stack of an insulator stressor plug and a silicon oxide plug in said trench, wherein said insulator stressor plug abuts said portion of said handle substrate exposed at said bottom of said trench, wherein said silicon oxide plug is substantially coplanar with a top surface of said at least one top semiconductor portion and has sidewalls in direct contact with sidewalls of said trench, and wherein an interface between said insulator stressor plug and said silicon oxide plug is coplanar with said bottom surface of said buried insulating layer.

2. The method of claim 1, further comprising:

forming a stack of pad layers directly on said SOI substrate; applying a photoresist on said stack of pad layers and lithographically patterning said photoresist; and transferring a pattern in said photoresist into said stack of pad layers and said SOI substrate by at least one reactive etch.

3. The method of claim 1, wherein said insulator stressor plug comprises a silicon nitride.

4. The method of claim 3, wherein the insulator stressor plug applies a compressive stress or a tensile stress to said at least one top semiconductor portion.

5. The method of claim 3, wherein said insulator stressor plug is formed by a deposition process selected from the group consisting of plasma enhanced chemical vapor depo-

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sition (PECVD), high density plasma chemical vapor deposition (HDPCVD), rapid thermal chemical vapor deposition (RTCVD), low pressure chemical vapor deposition (LPCVD), and a combination thereof.

6. The method of claim 1, wherein said forming said stack of said insulator stressor plug and said silicon oxide plug in said trench comprises:

depositing a stress-generating material into said trench; recessing said stress-generating material in said trench to form said insulator stressor plug; depositing a silicon oxide into said trench on top of said insulator stressor plug; and recessing said silicon oxide in said trench to form said silicon oxide plug.

7. The method of claim 6, wherein said recessing of said silicon oxide comprises reactive ion etching (RIE).

8. The method of claim 1, wherein a thickness of said at least one top semiconductor portion is from about 5 nm to about 300 nm.

9. The method of claim 8, wherein a depth of said trench is from about 200 nm to about 8,000 nm.

10. A method of forming a semiconductor structure comprising:

providing a semiconductor-on-insulator (SOI) substrate including a handle substrate consisting of a single crystalline semiconductor material, a buried insulator layer present on said handle substrate, and a top semiconductor layer present on said buried insulator layer;

forming a trench extending from a top surface of said top semiconductor layer of said SOI substrate into said handle substrate of said SOI substrate, wherein said trench laterally abuts and encloses at least one top semiconductor portion formed in said top semiconductor layer of said SOI substrate;

depositing a silicon nitride into said trench to completely fill said trench;

recessing said silicon nitride in said trench such that a top surface of said silicon nitride is coplanar with a bottom surface of said buried insulator layer to form an insulator stressor plug, said insulator stressor plug spanning an entire width of said trench; and

forming a silicon oxide plug over said insulator stressor plug in said trench, said silicon oxide plug having a top surface substantially coplanar with said top surface of said top semiconductor layer.

11. The method of claim 10, wherein said insulator stressor plug applies a compressive stress or a tensile stress to said at least one top semiconductor portion.

12. The method of claim 10, wherein said insulator stressor plug is formed by a deposition process selected from the group consisting of plasma enhanced chemical vapor deposition (PECVD), high density plasma chemical vapor deposition (HDPCVD), rapid thermal chemical vapor deposition (RTCVD), low pressure chemical vapor deposition (LPCVD), and a combination thereof.

13. The method of claim 10, wherein a thickness of said at least one top semiconductor portion is from about 5 nm to about 300 nm.

14. The method of claim 10, wherein a depth of said trench is from about 200 nm to about 8,000 nm.

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